Design of Digital Circuits

Lecture 26: Epilogue

Prof. Onur Mutlu
ETH Zurich

Spring 2019

31 May 2019

No Required Readings (for this lecture)

Recall: Major High-Level Goals of This Course

- In Digital Circuits & Computer Architecture

- Understand the basics
- Understand the principles (of design)
- Understand the precedents

- Based on such understanding:
  - learn how a modern computer works underneath
  - evaluate tradeoffs of different designs and ideas
  - implement a principled design (a simple microprocessor)
  - learn to systematically debug increasingly complex systems
  - Hopefully enable you to develop novel, out-of-the-box designs

- The focus is on basics, principles, precedents, and how to use them to create/implement good designs

Recall: Why These Goals?

- Because you are here for a Computer Science degree

- Regardless of your future direction, learning the principles of digital design & computer architecture will be useful to
  - design better hardware
  - design better software
  - design better systems
  - make better tradeoffs in design
  - understand why computers behave the way they do
  - solve problems better
  - think "in parallel"
  - think critically
  - …

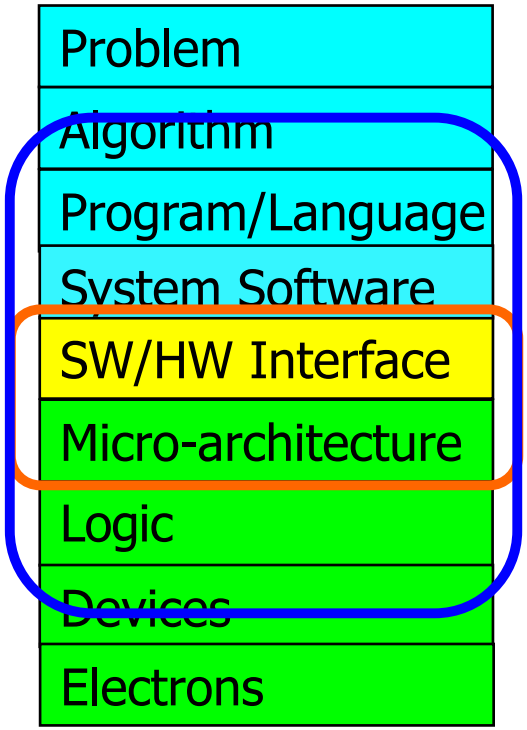
We Have Come A Long Way

- Started from Transistor as the Building Block
- Logic Design
- ISA and Microarchitecture
- Key Execution Paradigms
- The Memory System
- Built up to System Software Mechanisms

- Takeaway 1: All we covered is real and used in real systems → increasingly important
- Takeaway 2: Principles we covered apply broadly
- Takeaway 3: Tradeoff analysis and critical thinking that you are exposed to apply even more broadly

The Transformation Hierarchy

Computer Architecture (expanded view)



Computer Architecture (narrow view)

The Best Way to Approach This Course

- Take it as **a learning and growth experience**… all of it
- What we saw changed the world & endured the test of time…
- And, it will be more important…
- You may not all be future architects, but…
  - your development and thinking can greatly benefit from the concepts, tradeoffs, principles, critical thinking…
- **Focus on understanding, learning, critical analysis**

  → these are the agents for your growth

  → the course is designed to activate these agents

What We Did Not Cover

Computer Architecture is Very Rich

- Many ideas, much creativity, many tradeoffs and problems
- As scaling, performance, energy, reliability, security issues become worse in circuits and in software, computer architecture will be more and more important
- Already obvious in
  - AI/ML accelerators
  - Hardware security issues
  - Novel execution paradigms: Processing in memory
  - …
- See my ETH inaugural lecture
  - https://www.youtube.com/watch?v=kgiZlSOcGFM

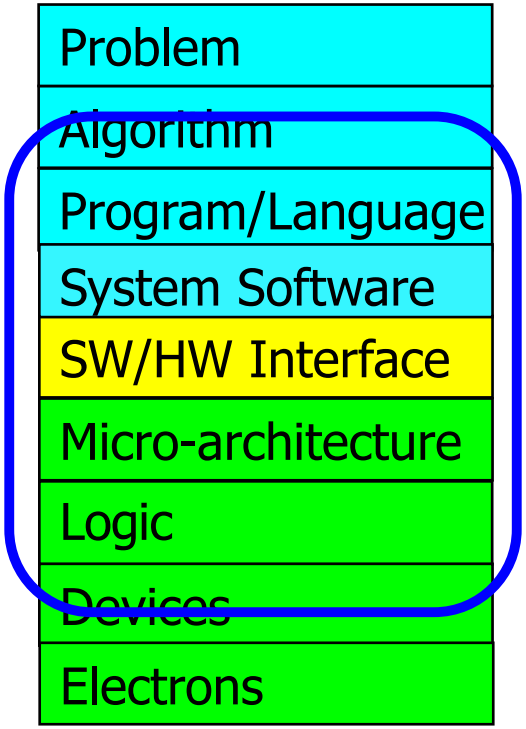
Recall from Lecture 2: Some Takeaways

- It is an exciting time to be understanding and designing computing platforms
- Many challenging and exciting problems in platform design
  - That noone has tackled (or thought about) before
  - That can have huge impact on the world's future
- Driven by huge hunger for data and its analysis ("Big Data"), new applications, ever-greater realism, …
  - We can easily collect more data than we can analyze/understand
- Driven by significant difficulties in keeping up with that hunger at the technology layer
  - Three walls: Energy, reliability, complexity

State of the Art

- This is a great time to be a computer architect

- Circuits strained
- Applications ever more demanding
- Multiple possible emerging technologies
- Many requirements, many systems
- Many, many security, reliability issues
- …



Many big innovations require computer architecture

Many Other Ideas and Topics

- Prefetching
- Runahead execution: Efficient latency tolerance
- Emerging memory technologies
- Solid state disks and storage, I/O
- Interconnection networks
- Many issues in multiprocessing and multithreading
- Heterogeneous multiprocessors
- QoS and predictable performance
- Reliable architectures
- Secure architectures
- Programmability, portability
- Better HW/SW interfaces
- Reconfigurable computing
- Heterogeneous CPU-GPU-FPGA-HWAcc architectures
- Specialized and domain-specific architectures – genomics, medicine, health, AI/ML
- Unconventional architectures – nature-inspired, quantum, molecular, …
- …

Oculus, New York City

Source: https://www.dezeen.com/2016/08/29/santiago-calatrava-oculus-world-trade-center-transportation-hub-new-york-photographs-hufton-crow/

Prefetching

Prefetching

- Idea: Fetch the data before it is needed (i.e. pre-fetch) by the program

- Why?
  - Memory latency is high. If we can prefetch accurately and early enough we can reduce/eliminate that latency.
  - Can eliminate compulsory cache misses
  - Can it eliminate all cache misses? Capacity, conflict?

- Involves predicting which address will be needed in the future
  - Works if programs have predictable miss address patterns

Prefetching: The Four Questions

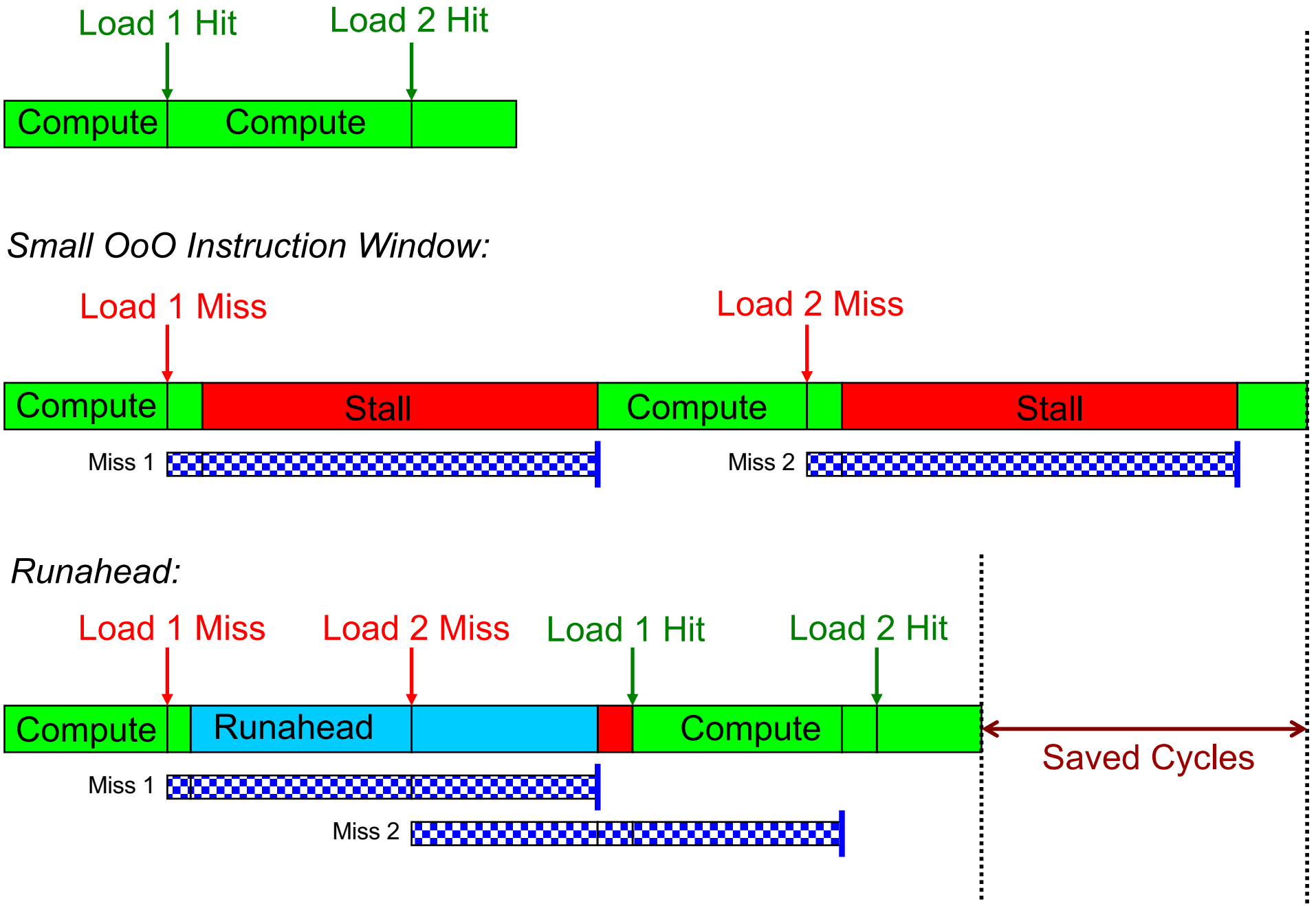
- What
  - What addresses to prefetch
- When
  - When to initiate a prefetch request
- Where
  - Where to place the prefetched data
- How
  - Software, hardware, execution-based, cooperative, …

Outline of Prefetching Issues…

- Why prefetch? Why could/does it work?
- The four questions
  - What (to prefetch), when, where, how
- Software prefetching
- Hardware prefetching algorithms
- Execution-based prefetching
- Prefetching performance
  - Coverage, accuracy, timeliness
  - Bandwidth consumption, cache pollution
- Prefetcher throttling
- Issues in multi-core
- Prefetching in new execution paradigms

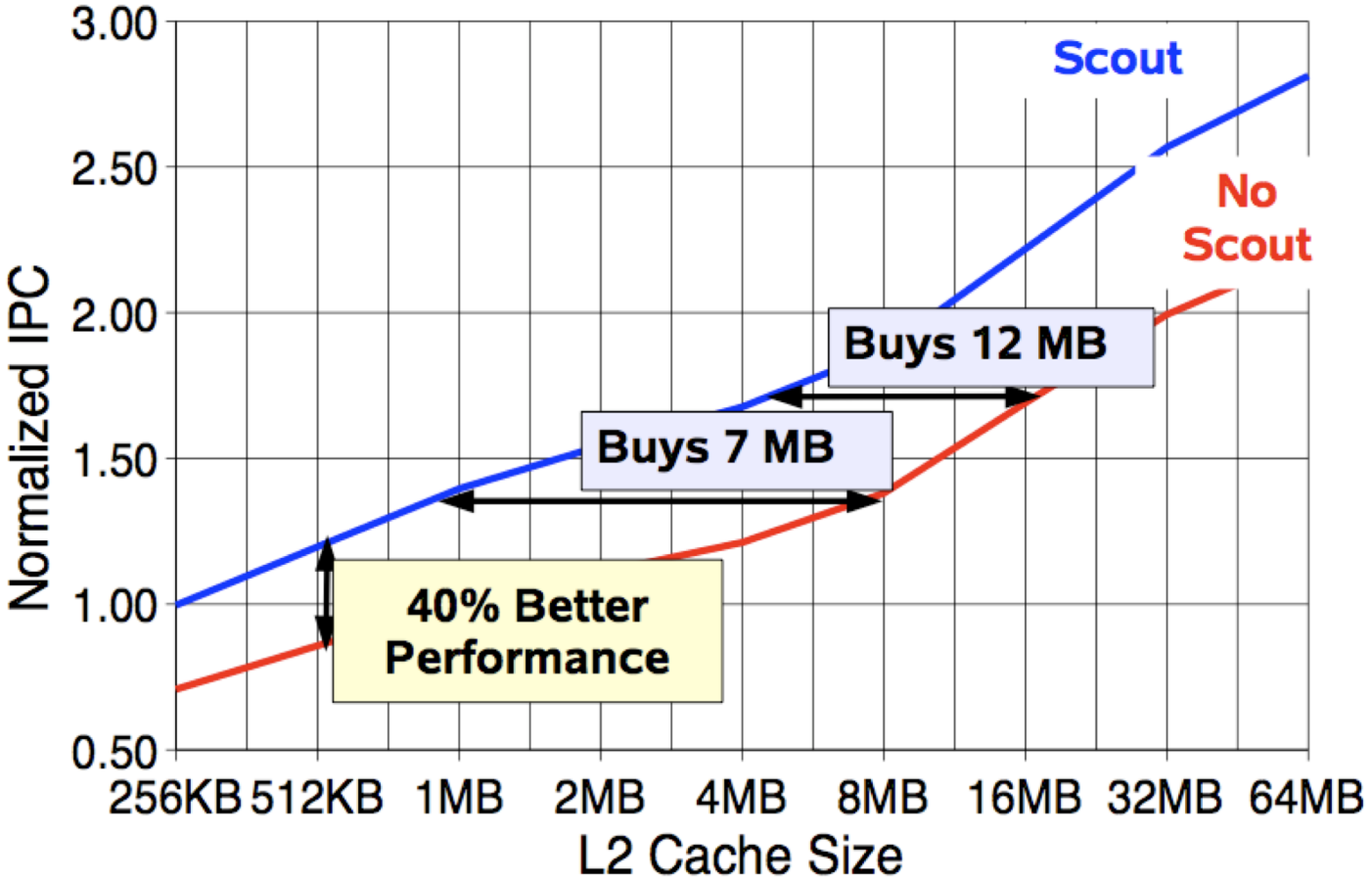
Runahead Execution

Runahead Execution Example



Effect of Runahead in Sun ROCK

- Shailender Chaudhry talk, Aug 2008.



More on Runahead Execution

- Onur Mutlu, Jared Stark, Chris Wilkerson, and Yale N. Patt, **"Runahead Execution: An Alternative to Very Large Instruction Windows for Out-of-order Processors"** *Proceedings of the 9th International Symposium on High-Performance Computer Architecture* (***HPCA***), pages 129-140, Anaheim, CA, February 2003. Slides (pdf)

Runahead Execution: An Alternative to Very Large Instruction Windows for Out-of-order Processors

Onur Mutlu § Jared Stark † Chris Wilkerson ‡ Yale N. Patt §

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The University of Texas at Austin
{onur,patt}@ece.utexas.edu

†Microprocessor Research
Intel Labs
jared.w.stark@intel.com

‡Desktop Platforms Group
Intel Corporation
chris.wilkerson@intel.com

More on Runahead Execution (Short)

- Onur Mutlu, Jared Stark, Chris Wilkerson, and Yale N. Patt, **"Runahead Execution: An Effective Alternative to Large Instruction Windows"** *IEEE Micro, Special Issue: Micro's Top Picks from Microarchitecture Conferences* (***MICRO TOP PICKS***), Vol. 23, No. 6, pages 20-25, November/December 2003.

Runahead Readings

- Required
  - Mutlu et al., "Runahead Execution", HPCA 2003, Top Picks 2003.
- Recommended
  - Mutlu et al., "Efficient Runahead Execution: Power-Efficient Memory Latency Tolerance," ISCA 2005, IEEE Micro Top Picks 2006.
  - Mutlu et al., "Address-Value Delta (AVD) Prediction," MICRO 2005.
  - Armstrong et al., "Wrong Path Events," MICRO 2004.

If You Want More of This…

Multiple Future Options

- Take the Bachelor's Seminar in Comp Arch
  - Offered every Fall and Spring
  - https://safari.ethz.ch/architecture_seminar/fall2018/doku.php

- Take the Computer Architecture course
  - Offered every Fall
  - https://safari.ethz.ch/architecture/fall2018/doku.php

- Read the referenced papers methodically and critically
- Do research with us
  - https://safari.ethz.ch/

SAFARI Research Group

Think BIG, Aim HIGH!

https://safari.ethz.ch

Bachelor's Seminar in Computer Architecture

- Fall 2019
- 2 credit units

- **Rigorous seminar on fundamental and cutting-edge topics in computer architecture**
- Critical presentation, review, and discussion of seminal works in computer architecture
  - We will cover many ideas & issues, analyze their tradeoffs, perform **critical thinking** and brainstorming

- Participation, presentation, synthesis report
- You can register for the course online
- https://safari.ethz.ch/architecture_seminar/fall2018/doku.php

(Next) Computer Architecture Course

- Fall 2019
- 8 credit units

- **Introduces the basic components of a modern computing system (processors, memory, interconnects, storage).**
  - Covers the fundamental concepts of the different parts of modern computing systems.
  - Covers the latest trends by exploring the recent research in Industry and Academia.

- 2 exams (midterm & final), lab assignments, homeworks
- You can register for the course online
- https://safari.ethz.ch/architecture/fall2018/doku.php

Doing Research with Us

- If you are interested in learning more and doing research in Computer Architecture, three suggestions:
  - Email me with your interest (CC: Juan, Mohammed, Lois, Hasan)
  - Take the seminar course and the "Computer Architecture" course
  - Do readings and assignments on your own

- There are many exciting projects and research positions available, spanning:
  - Memory systems
  - Hardware security
  - GPUs, FPGAs, heterogeneous systems, …
  - New execution paradigms (e.g., in-memory computing)
  - Security-architecture-reliability-energy-performance interactions
  - Architectures for medical/health/genomics

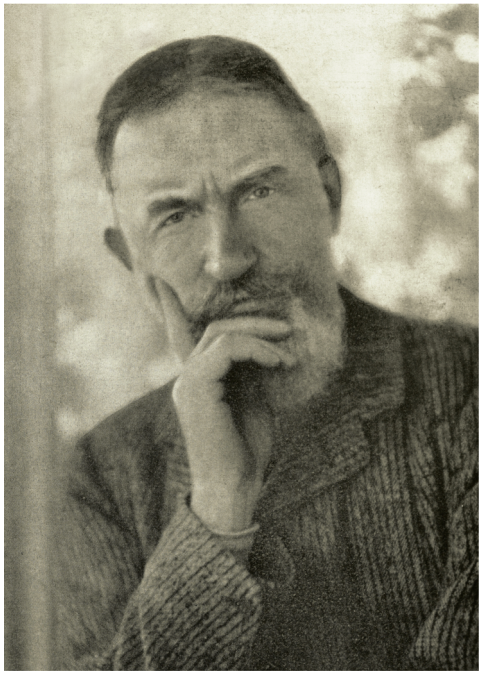
Food for Thought: Two Quotes

The reasonable man adapts himself to the world;

The unreasonable one persists in trying adapt the world to himself.

Therefore all progress depends on the unreasonable man.

George Bernard Shaw



Progress is impossible without change,
and those who cannot change their minds
cannot change anything.

Image: By Alvin Langdon Coburn - Illustrated London News, p. 575 (subscription required), PD-US, https://en.wikipedia.org/w/index.php?curid=49887931

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Research & Teaching: Some Overview Talks

https://www.youtube.com/watch?v=kgiZlSOcGFM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl

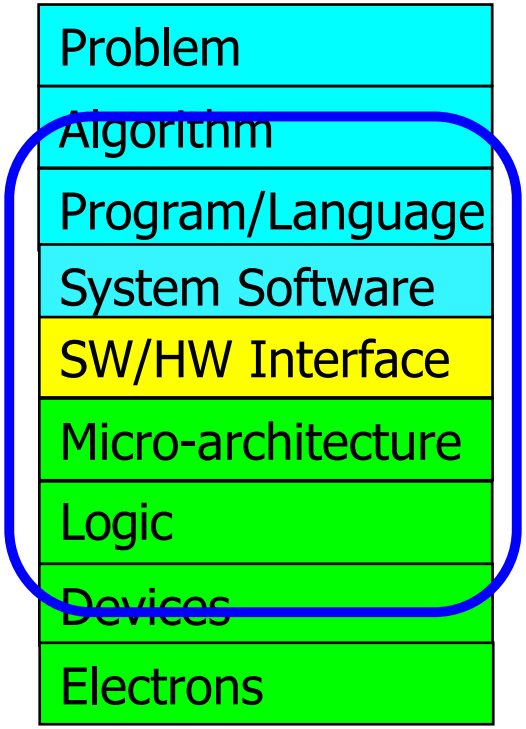
- Future Computing Architectures
  - https://www.youtube.com/watch?v=kgiZlSOcGFM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=1
- Enabling In-Memory Computation
  - https://www.youtube.com/watch?v=oHqsNbxgdzM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=7
- Accelerating Genome Analysis
  - https://www.youtube.com/watch?v=hPnSmfwu2-A&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=9
- Rethinking Memory System Design
  - https://www.youtube.com/watch?v=F7xZLNMIY1E&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=3

Research in Computer Architecture

State of the Art

- This is a great time to be a computer architect

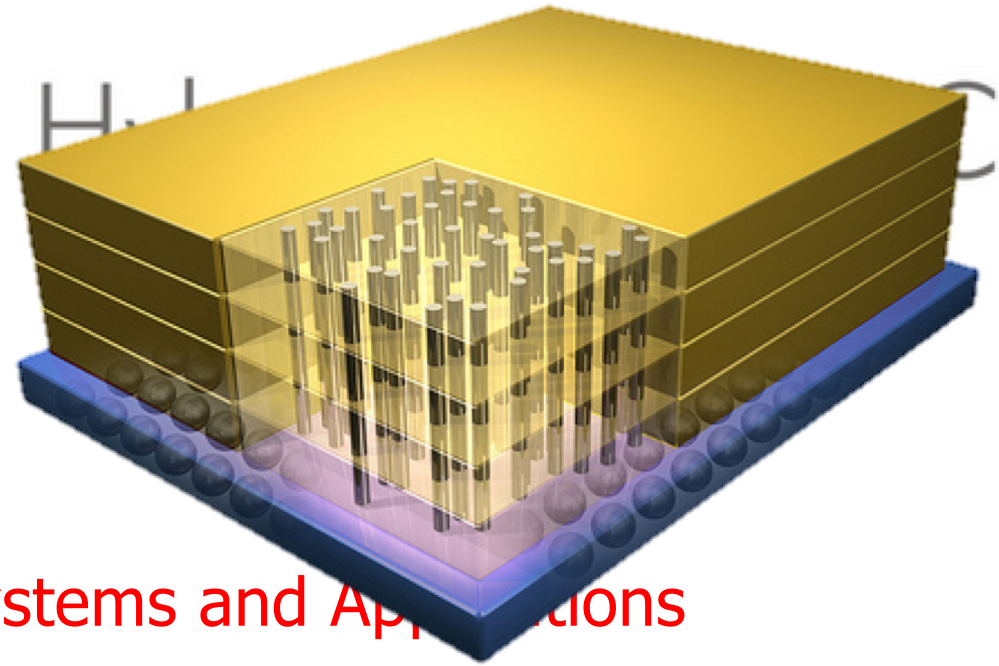
- Circuits strained
- Applications ever more demanding
- Multiple possible emerging technologies
- Many requirements, many systems
- Many, many security, reliability issues
- …



Many big innovations require computer architecture

Example: Why In-Memory Computation Today?

- Push from Technology

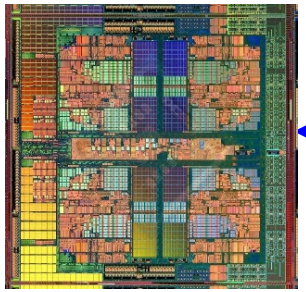


- Pull from Systems and Applications
  - Data access is a major system and application bottleneck
  - Systems are energy limited
  - Data movement much more energy-hungry than computation

Current Research Focus Areas

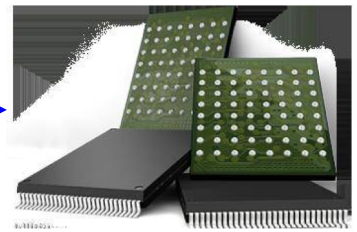
***Research Focus:* Computer architecture, HW/SW, security, bioinformatics**

- *Memory and storage (DRAM, flash, emerging), interconnects*
- *Heterogeneous & parallel systems, GPUs, systems for data analytics*
- *System/architecture interaction, new execution models, new interfaces*
- *Energy efficiency, fault tolerance, hardware security, performance*
- *Genome sequence analysis & assembly algorithms and architectures*
- *Biologically inspired systems & system design for bio/medicine*

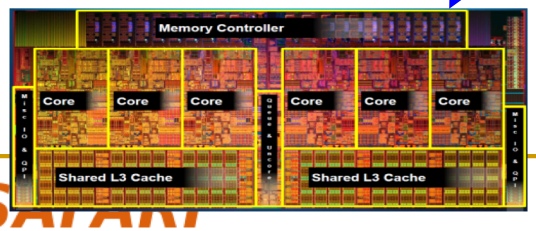


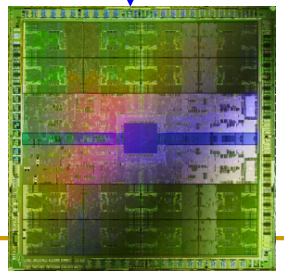
Heterogeneous Processors and Accelerators

Hybrid Main Memory



Persistent Memory/Storage





General Purpose GPUs

Broad research spanning apps, systems, logic with architecture at the center

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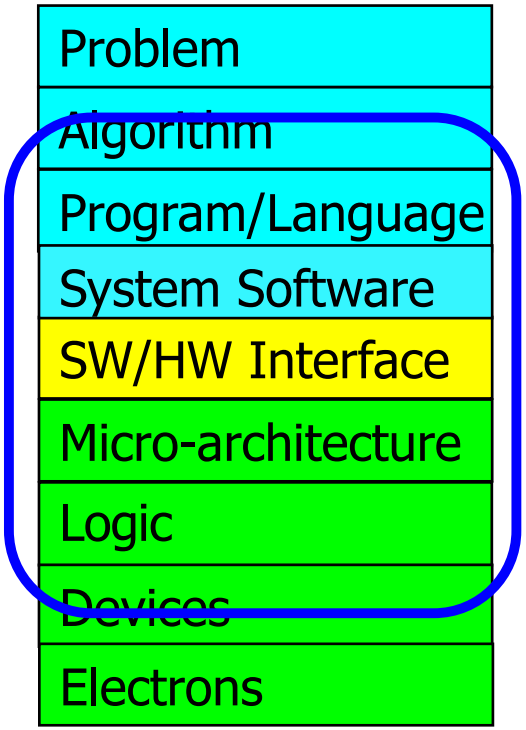
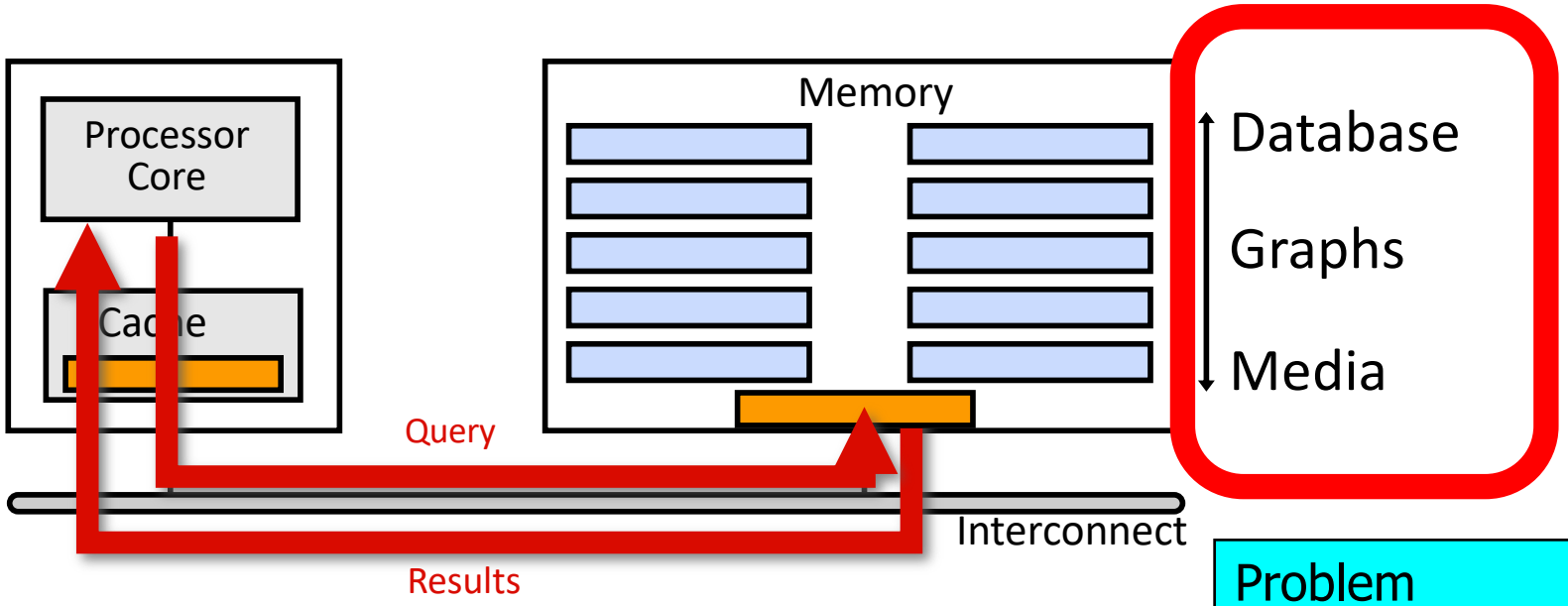
Four Key Current Directions

- Fundamentally Secure/Reliable/Safe Architectures
- Fundamentally Energy-Efficient Architectures
  - Memory-centric (Data-centric) Architectures
- Fundamentally Low-Latency Architectures
- Architectures for Genomics, Medicine, Health

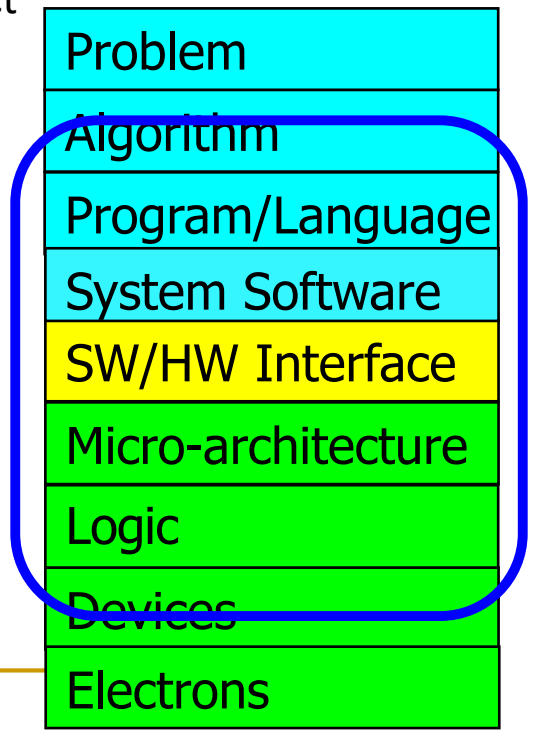
Research Across the Stack



One Example: Processing Inside Memory



- Many questions … How do we design the:
  - compute-capable memory & controllers?
  - processor chip?
  - software and hardware interfaces?
  - system software and languages?
  - algorithms?



In-Memory DNA Sequence Analysis

- Jeremie S. Kim, Damla Senol Cali, Hongyi Xin, Donghyuk Lee, Saugata Ghose, Mohammed Alser, Hasan Hassan, Oguz Ergin, Can Alkan, and Onur Mutlu,
  "GRIM-Filter: Fast Seed Location Filtering in DNA Read Mapping Using Processing-in-Memory Technologies"
  to appear in ***BMC Genomics***, 2018.
  *to also appear in Proceedings of the 16th Asia Pacific Bioinformatics Conference (**APBC**)*, Yokohama, Japan, January 2018.
  arxiv.org Version (pdf)

GRIM-Filter: Fast Seed Location Filtering in DNA Read Mapping Using Processing-in-Memory Technologies

Jeremie S. Kim[1,6*], Damla Senol Cali[1], Hongyi Xin[2], Donghyuk Lee[3], Saugata Ghose[1], Mohammed Alser[4], Hasan Hassan[6], Oguz Ergin[5], Can Alkan*[4], and Onur Mutlu*[6,1]

New Genome Sequencing Technologies

Nanopore Sequencing Technology and Tools: Computational Analysis of the Current State, Bottlenecks, and Future Directions

Damla Senol Cali [1,*], Jeremie Kim [1,3], Saugata Ghose [1], Can Alkan [2*] and Onur Mutlu [3,1*]

[1] Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, USA
[2] Department of Computer Engineering, Bilkent University, Bilkent, Ankara,Turkey
[3] Department of Computer Science, Systems Group, ETH Zürich, Zürich, Switzerland

Some Basics of Research

How To Do Research & Advanced Dev.

- We will talk a lot about this in this course

- Learning by example
  - Reading and evaluating strong and seminal papers & designs

- Learning by doing
  - Semester-long research/design projects, masters' projects, PhD thesis

- Learning by open, critical discussions
  - Paper reading groups, frequent brainstorming and discussions
  - Design sessions
  - Collaborations

What Is The Goal of Research?

- To generate new insight
  - that can enable what previously did not exist

- Research is a hunt for insight that can eventually impact the world

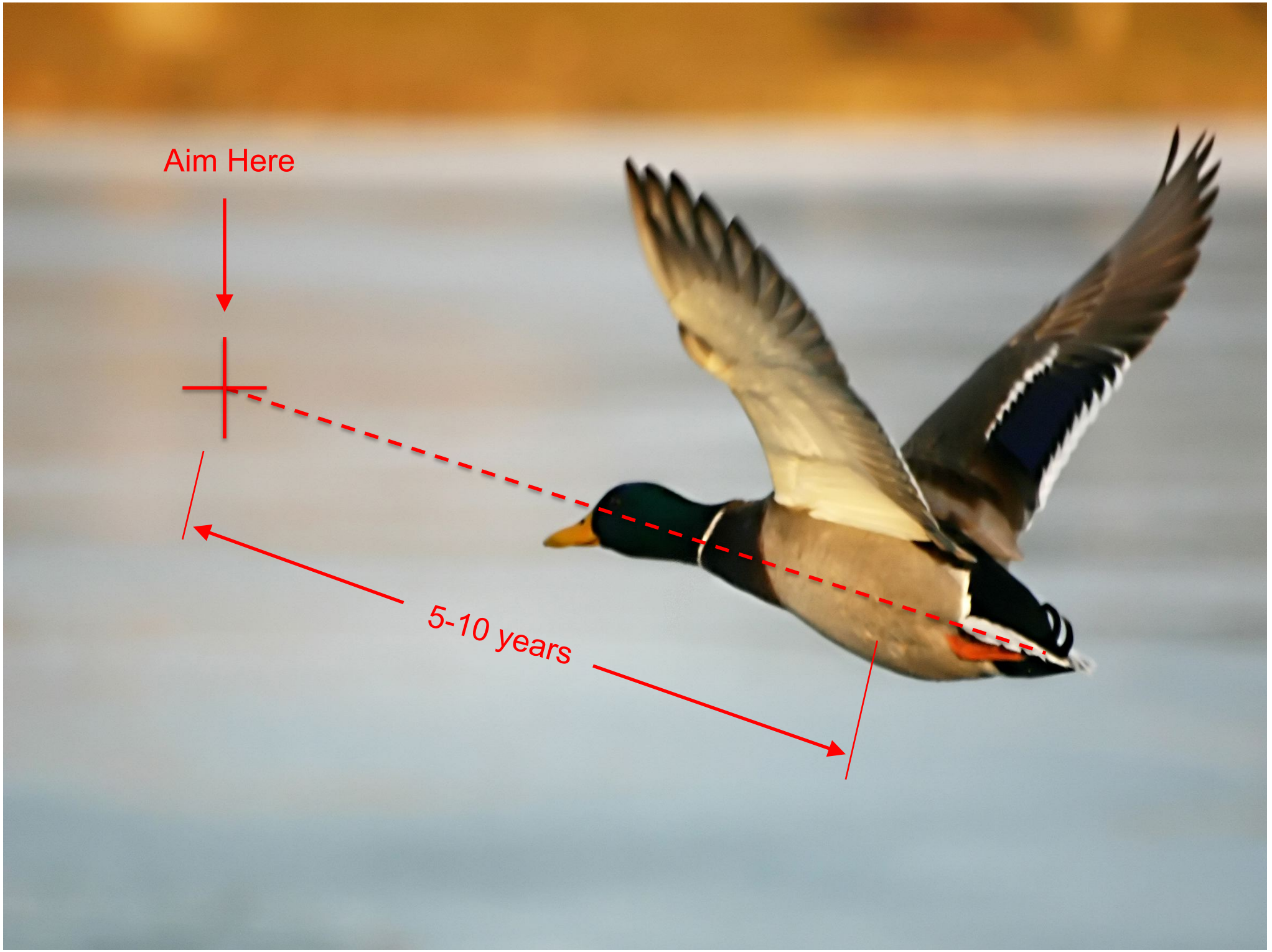
Some Basic Advice for Good Research

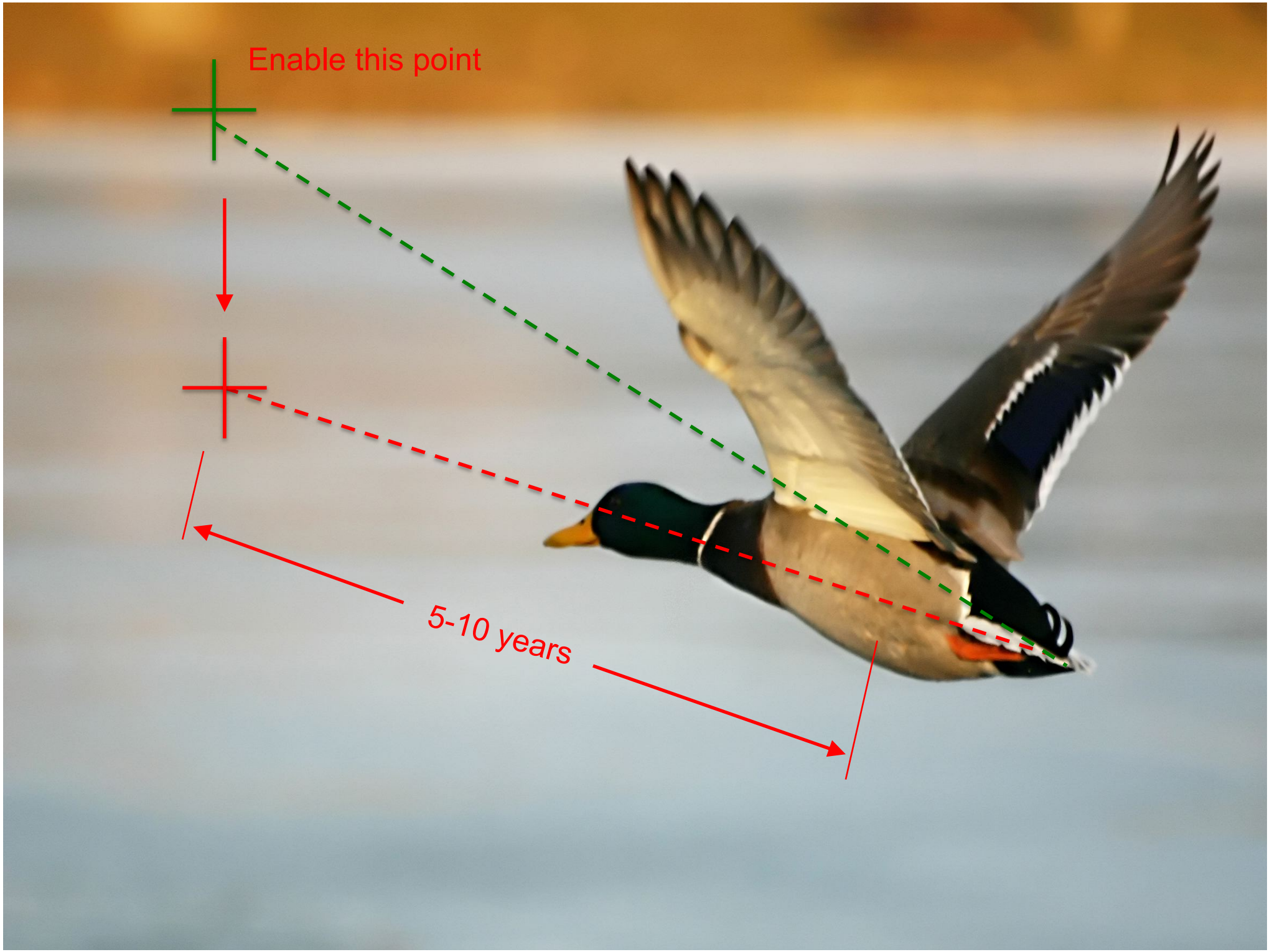
- Choose great problems to solve: Have great taste
  - Difficult
  - Important
  - High impact
- Read heavily and critically
- Think big (out of the box)
  - Do not restrain yourself to tweaks or constraints of today
  - Yet, think about adoption issues
- Aim high
- Write and present extremely well


Looking here for lost keys

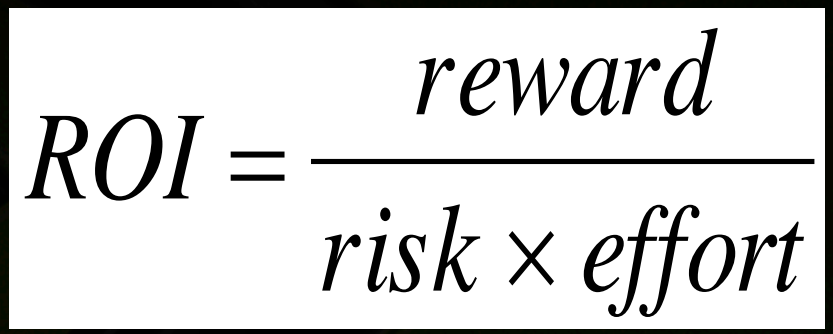

Lost keys here
Looking here


Current Architecture Practice


Aim Here
5-10 years


Enable this point
5-10 years

The Research Formula



Reward

If you are wildly successful, what difference will it make?

$$ROI = \frac{reward}{risk \times effort}$$

Effort

Learn as much as possible with as little work as possible

$$ROI = \frac{reward}{risk \times effort}$$

Effort

Do the minimum analysis and experimentation necessary to make a point

$$ROI = \frac{reward}{risk \times effort}$$

Research is a
hunt for insight

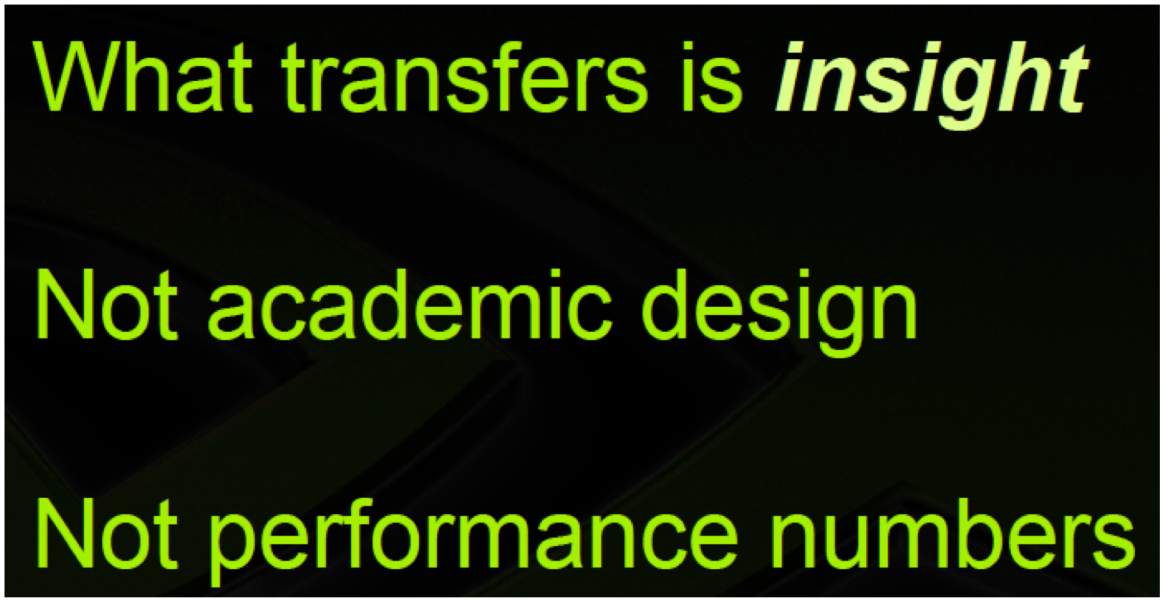
Need to get off the beaten path to find new insights

Recommended Talk

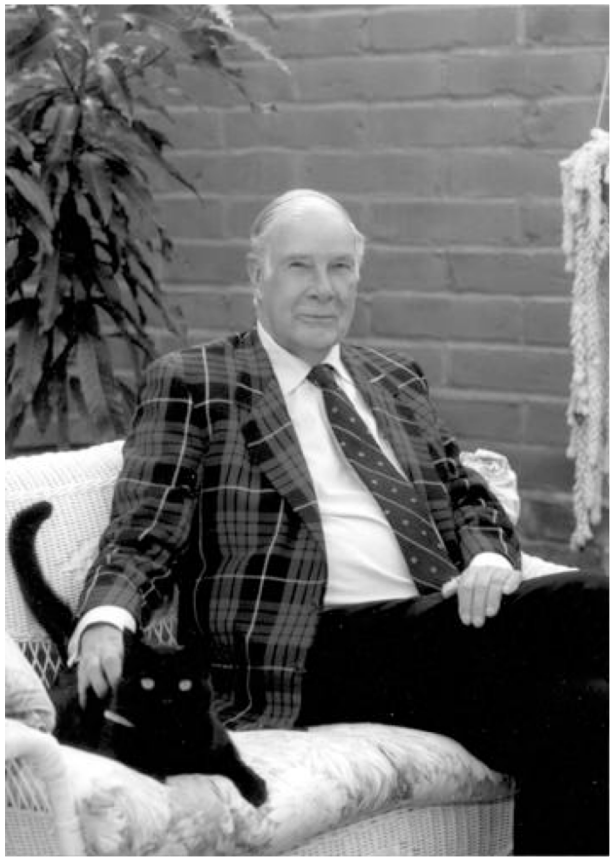
- Bill Dally, Moving the needle: Effective Computer Architecture Research in Academy and Industry

  ISCA 2010 Keynote Talk.

- Acknowledgment: Past few slides are from this talk



More Good Advice



"The purpose of computing is insight, not numbers"

Richard Hamming

Some Personal Examples

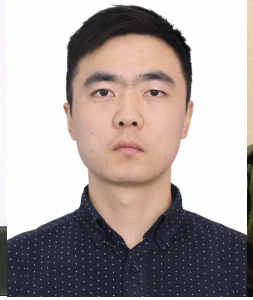
Brief Self Introduction

- Onur Mutlu
  - Full Professor @ ETH Zurich CS, since September 2015 (officially May 2016)
  - Strecker Professor @ Carnegie Mellon University ECE/CS, 2009-2016, 2016-…
  - PhD from UT-Austin, worked at Google, VMware, Microsoft Research, Intel, AMD
  - https://people.inf.ethz.ch/omutlu/
  - omutlu@gmail.com (Best way to reach me)
  - https://people.inf.ethz.ch/omutlu/projects.htm
- Research and Teaching in:
  - Computer architecture, computer systems, hardware security, bioinformatics
  - Memory and storage systems
  - Hardware security, safety, predictability; fault tolerance
  - Hardware/software cooperation
  - Architectures for bioinformatics, health, medicine
  - New computation, communication, storage paradigms
  - …

SAFARI Group Members @ ETH Zurich


Dr. Mohammed Alser


Dr. Lois Orosa


Dr. Yaohua Wang


Dr. Juan Gómez-Luna

- 4 Post-doctoral Researchers
- 8 PhD Students + 4 at CMU
- 5 Interns
- 15 Master's and Bachelor's Researchers


Jeremie Kim


Hasan Hassan


Minesh Patel


Ivan Puddu


Lukas Breitwieser

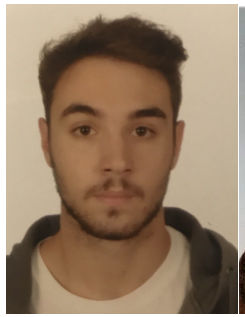

Giray Yaglikci


Can Firtina


Geraldo F. de Oliveira

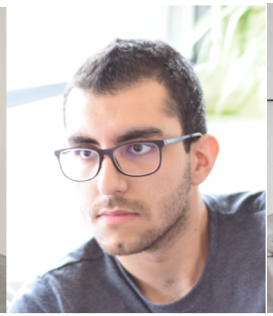

Nika Mansouri


Skanda Koppula

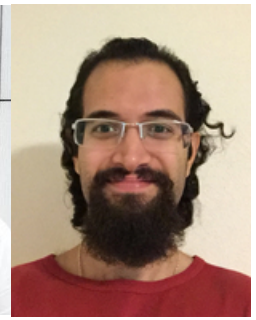

Konstantinos Kanellopoulos


Nisa Bostanci


Ataberk Olgun


Rokneddin Azizi


Christina Giannoula


Taha Shahroodi

Teaching: Accelerated Memory Course (~6.5 hours)

- ACACES 2018
  - Memory Systems and Memory-Centric Computing Systems
  - Taught by Onur Mutlu July 9-13, 2018
  - ~6.5 hours of lectures

- Website for the Course including Videos, Slides, Papers
  - https://people.inf.ethz.ch/omutlu/acaces2018.html
  - https://www.youtube.com/playlist?list=PL5Q2soXY2Zi-HXxomthrpDpMJm05P6J9x

- All Papers are at:
  - https://people.inf.ethz.ch/omutlu/projects.htm
  - Final lecture notes and readings (for all topics)

Teaching: Online Courses and Lectures

- **Freshman Digital Circuits and Computer Architecture Course Lecture Videos (2018, 2017)**
- **Graduate Computer Architecture Course Lecture Videos (2018, 2017, 2015, 2013)**
- **Undergraduate Computer Architecture Course Lecture Videos (2015, 2014, 2013)**
- **Parallel Computer Architecture Course Materials (Lecture Videos)**
- https://people.inf.ethz.ch/omutlu/teaching.html
- https://www.youtube.com/channel/UCIwQ8uOeRFgOEvBLYc3kc3g
- https://www.youtube.com/user/cmu18447

Research & Teaching: Some Overview Talks

https://www.youtube.com/watch?v=kgiZlSOcGFM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl

- Future Computing Architectures
  - https://www.youtube.com/watch?v=kgiZlSOcGFM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=1
- Enabling In-Memory Computation
  - https://www.youtube.com/watch?v=oHqsNbxgdzM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=7
- Accelerating Genome Analysis
  - https://www.youtube.com/watch?v=hPnSmfwu2-A&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=9
- Rethinking Memory System Design
  - https://www.youtube.com/watch?v=F7xZLNMIY1E&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=3